

Analog time-reversed ultrasonically encoded light focusing inside scattering media with a 33,000× optical power gain

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Supplementary note

Signal-to-noise ratio (SNR) of optical detection

If the incident optical illumination generates an average photocurrent \bar{i}_s , the amplitude SNR of the photodetector output is²⁹

$$SNR = \frac{\bar{i}_s}{\sqrt{\left[2e\bar{i}_s + 2e\bar{i}_b + \frac{4k_B T}{R_L} \right] \Delta \nu}}, \quad (S1)$$

where e is the elementary charge, \bar{i}_b is the average reverse bias leakage current, k_B is the Boltzmann constant, T is the absolute temperature, R_L is the load resistance and $\Delta \nu$ is the bandwidth of the detector. The three terms on the denominator account for the signal shot noise, dark-current shot noise, and thermal noise.

A pulse with a duration τ_p has a bandwidth of $\Delta \nu \approx 1/(2\tau_p)$. Denoting the pulse energy as E_p , the bandwidth can be expressed in terms of E_p as

$$\Delta \nu = \frac{\bar{i}_s}{2E_p \rho_d}, \quad (S2)$$

where ρ_d denotes the photodetector's responsivity. Inserting Eq. (S2) in (S1) we get

$$SNR = \sqrt{\frac{E_p}{\frac{\alpha}{\bar{P}} + \beta}}. \quad (S3)$$

In Eq. (S3), $\alpha = (e\bar{i}_b + 2k_B T / R_L) / \rho_d^2$ and $\beta = e / \rho_d$ are constants, and \bar{P} denotes the average power of the pulse (E_p / τ_p).

Reference

- 29 Yariv, A. & Yeh, P. *Photonics: Optical Electronics in Modern Communications* (*The Oxford Series in Electrical and Computer Engineering*). (Oxford University Press, Inc., 2006).

Supplementary figure

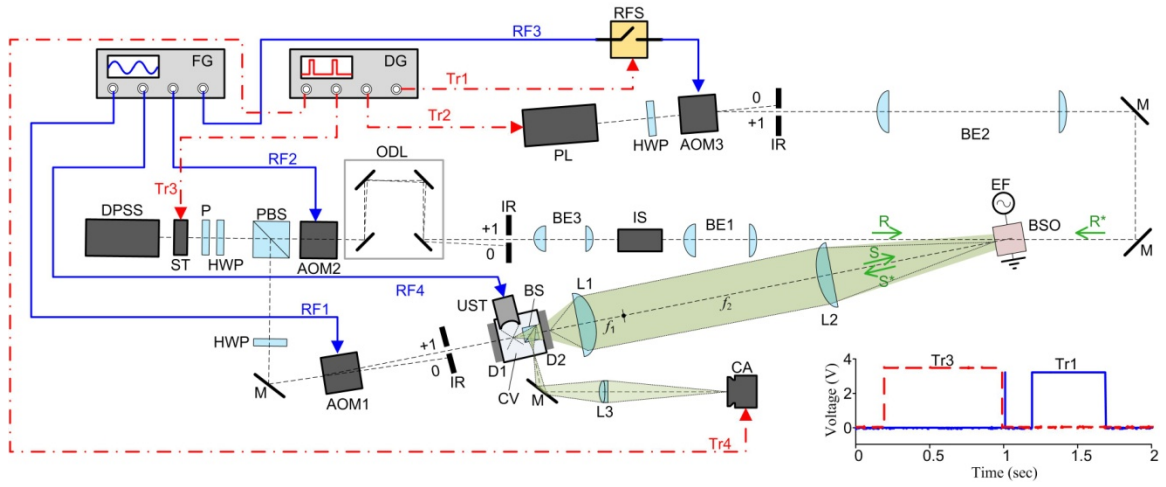


Figure S1. System setup. AOM, acousto-optic modulator; BE, beam expander; BS, 50:50 non-polarizing beamsplitter; BSO, $\text{Bi}_{12}\text{SiO}_{20}$ crystal; CA, CMOS camera or photodiode; CV, water-containing cuvette; D, diffuser; DG, delay generator; DPSS, diode-pumped solid-state laser; EF, externally applied field; FG, function generator; HWP, half-wave plate; IR, iris; IS, optical isolator; L, lens; M, mirror; ODL, optical delay line; P, optical polarizer; PBS, polarizing beamsplitter; PL, pulsed laser; RF, radio-frequency driving signal; RFS, radio-frequency switch; ST, optical shutter; Tr, trigger signal; UST, ultrasonic transducer. Inset: oscilloscope traces of Tr1 and Tr3.